EFFECTS OF RESIDUAL CARBON ON DEPOSITION IN COAL-FIRED GAS TURBINES

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ABSTRACT

The influence of residual carbon in coal ash on ash deposition at coal-fired gas turbine conditions has been investigated. Measurements of sticking coefficients (fraction of impacting ash particles that adhere) and ash deposit adhesion strength in a laminar-flow drop tube furnace indicate that high carbon levels in ash can decrease sticking fractions. However, high carbon levels also increased the adhesion strength of ash deposits, making them more difficult to remove. Possible mechanisms for the involvement of carbon in ash deposit formation are presented.

INTRODUCTION

The U.S. Department of Energy is currently sponsoring a program to develop direct coal-fired gas turbines. Direct coal-fired gas turbines are potentially attractive alternatives to conventional steam cycle electric power generation because of their higher efficiencies. However, the high mineral matter content of coal creates problems with deposition, erosion, and corrosion of turbine components. Ash deposits are formed in turbines by the adherence of ash particles to the surfaces of stators and blades. During combustion, components of the coal ash become molten and thus readily adhere to turbine components upon impaction. The tendency of various coals to form ash deposits during combustion is a complex function of many variables including the ash chemistry, gas temperature and pressure, gas velocity, and the temperature of the turbine components. Previous test results from this laboratory[1-2], from bench-scale combustor tests[3], and from tests on a gas turbine simulator[4-5] have indicated that unburned carbon in coal ash may affect the degree of deposit formation. The present study was initiated to further explore the effects of carbon on mechanisms of ash deposit formation.

Particulate in the products of combustion (POC) streams entering direct coal-fired gas turbines will probably contain much higher fractions of unburned carbon than for past coal experience such as in boilers. The lower ash levels for potential turbine fuels compared to boiler fuels result in higher percentages of carbon in the POC for a given combustion efficiency. Figure 1 illustrates this effect for 99% carbon burnout of a solid fuel such as coal. This figure indicates that unburned carbon would constitute about 50% of the POC particulate for a 1% ash coal turbine fuel, but only about 15% of the POC particulate for a coal boiler plant using a 5% ash coal.

Past tests have indicated a significant effect of unburned carbon on deposition; however, data from different tests appear to be contradictory. Tests associated with an early coal-fired gas turbine program[6] showed that the presence of relatively coarse incandescent (burning) coal particles in the gas stream increased the rate and density of deposit buildup. On the other hand, more recent cascade tests at General Electric with low ash coal water fuels showed much lower deposition rates occurred when the combustion efficiency was reduced and unburned carbon levels were high[4-5]. Analyses of data from tests at General Motors Allison Division[3] resulted in the hypothesis that increased carbon levels could increase deposition at the highest temperature locations in the turbine flowpath. This was attributed to unburned carbon producing larger particle sizes and higher delivery rates, higher particle impact and surface temperatures, and locally reducing conditions with relatively low melting ash phases. For the lower temperature regions of the turbine flowpath, it was hypothesized that carbon could reduce deposition by eroding previously retained ash material on the surfaces.

The experiments described in this paper were designed to assess the effects on deposition of relatively high POC carbon-ash-ratios for conditions representative of direct coal-fired gas turbines. The data are expected to be useful in identifying parameters that need to be controlled to alleviate deposition in coal-fired gas turbines.

EXPERIMENTAL

Experiments were performed in an electrically heated, laboratory scale drop-tube combustor designed to operate at temperatures up to 1400°C. This combustor[7], the Combustion/Deposition Entrained Reactor (CDER), is shown in Figure 2. Approximately 3-10 grams per hour of -400 mesh pulverized coal was entrained in 5 standard liters per minute (lpm) of air from a circulating feeder. A water-cooled injection probe was used to introduce this particle-laden flow into the combustor where it mixed with 25 lpm of preheated primary air. The coal feed rates used in these experiments allowed long sampling times during deposition tests which resulted in excellent time resolution of the growth of the ash deposits. The residence time of coal particles in the combustor were controlled by changes in the total gas flow, or the position of the injection probe. In tests reported here, the residence time was varied over a range of 440 to 640 milliseconds by adjusting the position of the injection probe. This produced ash with a range of carbon levels from approximately 10 to 50%. The tests were conducted at gas temperatures of 1100 and 1200°C, which is representative of current and future industrial gas turbine inlet temperatures.

Experiments in the CDER were designed to simulate deposition on the leading edge of a gas turbine airfoil where the primary mode of particle delivery to the surface of the airfoil is inertial impaction. At the exit of the combustion zone the products of combustion were accelerated through a 3.2 mm diameter nozzle, creating a jet which impinged on a flat, 12.7 mm diameter platinum disk. The resultant jet velocity of approximately 300 m/s is within the range expected in the first stage of a gas turbine. The platinum target was positioned 6 mm below the nozzle aperture (Figure 3). This nozzle/target configuration was developed according to procedures for inertial impactor design to insure that all particles larger than approximately 0.5 microns are forced by inertia to impact the target, as would occur on the leading edge of a gas turbine stator or blade. Platinum was used as an inert target material to eliminate surface reactions peculiar to a specific blade material which could affect the experimental results. The target could be cooled from the underside by an opposing jet of cooling air. Thus, a range of target temperatures were obtainable by varying the cooling air flow rate. The target temperature was measured throughout each test using a two-color optical pyrometer which monitored the temperature of the backside of the platinum target.

Sticking coefficients were measured by first passing the jet of exhaust through a filter to determine the total particle mass arrival rate. Gas flow through the filter (which was positioned in the same location as the target) was controlled via a vacuum pump and a mass flow controller. The rate of deposit buildup was determined by placing a target of known weight under the jet, and then withdrawing the target after a specified exposure period (usually ten minutes) to measure the weight gain. The sticking coefficient was calculated as the ratio of the weight gain of the target to the total mass arriving at the target (determined by the filter sample). The filter samples were quenched with cold air, resulting in unburned carbon in the samples. Since carbon was burned out of the deposits, filter samples were analyzed for carbon content to correct the ash arrival rate used to calculate the sticking coefficient.

Deposit adhesion strength (or shear strength) was measured using a device shown in Figure 4. The device consists of an alumina rod attached to a translation stage and linear actuator. A load cell is used to measure the force required to dislodge deposits from the targets using the blunt tip of the rod. The device is attached to the CDER, and the measurements are conducted at temperature. The measurements are in pounds of force, and are adjusted for the area of contact between the deposit and target to produce units of pounds per square inch.

DISCUSSION

The coal used in these tests was an Arkwright Pittsburgh bituminous containing approximately 7% ash and 2% sulfur. Ultimate and elemental analyses for the coal are shown in Table 1. Figure 5 shows measurements of sticking coefficients as a function of carbon levels in the ash at two gas temperatures. The data points are averages of a number of measurements collected on the same day at identical conditions. In Figure 6, the high and low data points are plotted along with the average to show the degree of scatter in the data. Figure 7 shows the trend in the sticking coefficient data compared to measurements of adhesion strength as a function of carbon.

The data show several significant effects of unburned carbon:

- Sticking fractions were highly sensitive to unburned carbon, decreasing by a factor of about seven when unburned carbon levels increased from 10 to 50%.
- Increased unburned carbon increased deposit adhesion strength.
- Carbon levels more significantly affected sticking fractions than changes in gas temperature from 1100 to 1200°C.

The following are proposed as possible mechanisms for the observed effects of unburned carbon. Unburned carbon may have a short term effect on sticking, and a long term effect on deposit strength. Some of the carbon may be captured by other molten material on the surface and oxidize under subsequent layers of deposits over longer periods of time (seconds or minutes) compared to the time frame of particle impacts (milliseconds). The increased temperatures and locally reducing conditions within the deposit could produce increased levels of molten phases and sintering to result in higher deposit strengths with increased carbon levels.

The sticking fraction of particles impacting at the outer deposit surfaces may be predominantly affected by the competition between capture of molten particles and erosion by harder particles. The ultimate sticking fraction may depend on factors affecting the balance of levels of molten phases versus hard materials (both the particles, and at the deposit outer surface). The levels of molten versus hard phases may be affected by the ash composition and local temperatures. The elevation in local temperature of both the impacting particles and the outer deposit surface due to oxidizing carbon may ultimately be limited by the local oxygen levels. In that case, additional carbon in the POC would not increase levels of molten ash phases, but would increase the amount of hard material to erode the deposit surface. This would cause a decrease in deposition with an increase in carbon levels as was observed in these experiments. And, since the local temperatures and levels of molten phases would be predominantly affected by local oxygen levels rather than gas temperature, the sticking fraction would not be strongly influenced by gas temperature as was observed in these experiments.

The increase in deposition with increased carbon levels mentioned previously for tests in an early direct coal-fired turbine program[4] may have involved changes in carbon fractions below levels where local oxygen concentrations limit the degree of melting. In that case, molten ash levels and sticking may be controlled by carbon fractions and would increase with increasing carbon levels.

SUMMARY AND CONCLUSIONS

Particulate in the POC streams entering direct coal-fired gas turbines will probably contain much higher fractions of unburned carbon than for past coal experience because of the use of beneficiated, low ash fuels. Measurements of ash sticking fractions and ash deposit adhesion strength in a drop tube combustor indicate that high levels of carbon in ash can reduce sticking fractions significantly, while also increasing the deposit strength. It is suggested that increased carbon levels may increase the amount of hard material relative to molten phases in the particulate when carbon oxidation is limited by local oxygen concentrations. However, heat generation from the burning carbon in deposited particulate in a locally reducing environment may cause increased levels of molten species and sintering, creating deposits that are more difficult to remove.

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Table 1. Coal Analyses

	Arkwright	Blue Gem
ULTIMATE ANALYSES		
% Ash	6.93	0.56
% Carbon	75.90	78.06
% Hydrogen	5.34	5.67
% Nitrogen	1.45	1.98
% Sulfur	2.03	0.99
ASH ANALYSES		
% SiO_2	48.09	16.86
% Al_2O_3	25.07	22.75
% Fe_2O_3	10.95	29.57
% TiO_2	1.27	1.95
% P_2O_5	0.18	0.48
% CaO	5.78	7.03
% MgO	1.25	2.46
% K_2O	1.16	0.53
% Na_2O	0.90	1.54
% SO_2	5.34	8.07
ASH FUSION TEMPERATURE (+/- 40°C)		
Initial Deformation	1,190	1,238
Softening	1,316	1,308
Hemispherical	1,356	1,371
Fluid	1,383	1,427

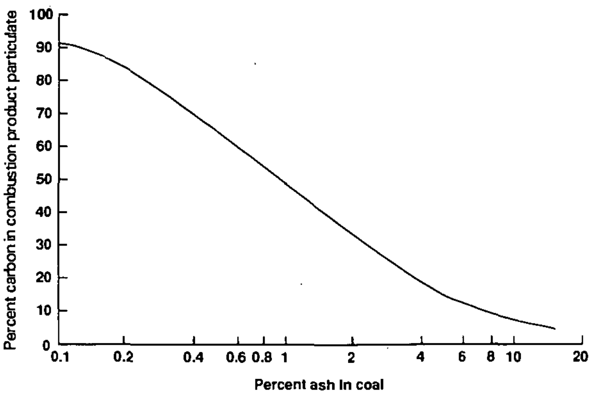

Figure 1: Percent of carbon in combustion particulate versus percent of ash in coal for 99% carbon burnout efficiency during combustion

Item	Test Section
PRESSURE, ABSOLUTE, atm	1-12
FLOW RATE, slpm	10-350
VESSEL LENGTH, cm	152
VESSEL OUTSIDE DIAMETER, cm	61
WALL THICKNESS, mm	95 (sch 40-304LSS)
PROCESS STREAM EXIT TEMPERATURE, °C	1,400
VESSEL SKIN TEMPERATURE, °C	< 150
ELEMENTAL TEMPERATURE (maximum), °C	1,650
HEATING ELEMENTS	KANTHAL SUPER 33 9/18
HEATER OUTPUT, watts	7,060
POWER SUPPLY, V/A	35/350
EXHAUST FLOW COMPOSITION	DILUTE COAL POC/ FILTERED
EXHAUST FLOW PRESSURE/TEMPERATURE	< 2 atm; < 200°C

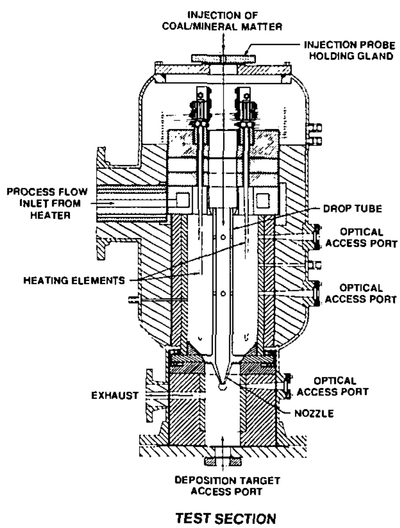

Figure 2: CDER System Design Specifications

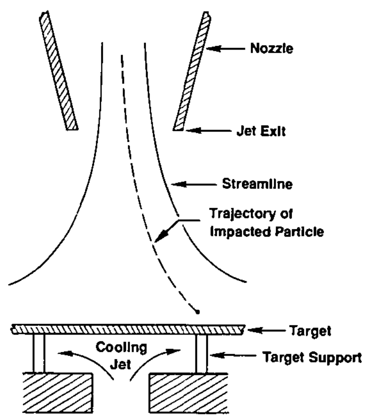

Figure 3: CDER Nozzle/Target Assembly

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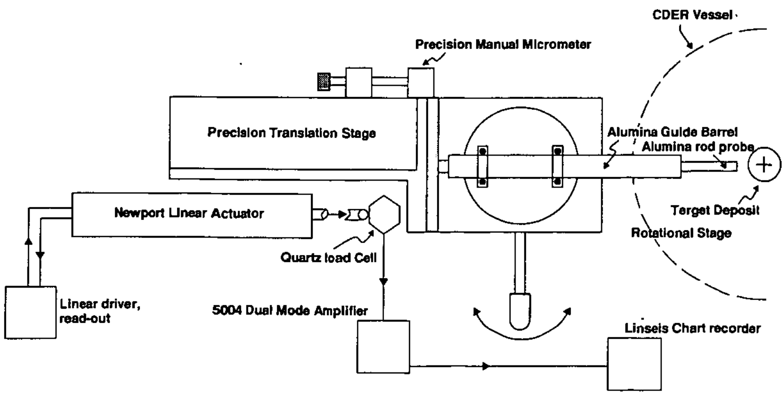

Figure 4: Adhesion Strength Meter

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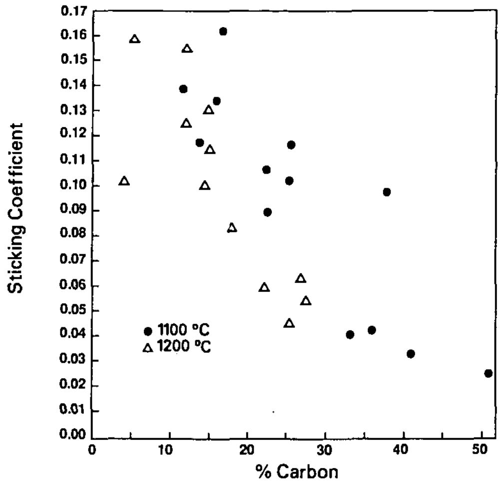

Figure 5: Sticking Coefficient vs % Carbon in Ash, Arkwright Bituminous Coal

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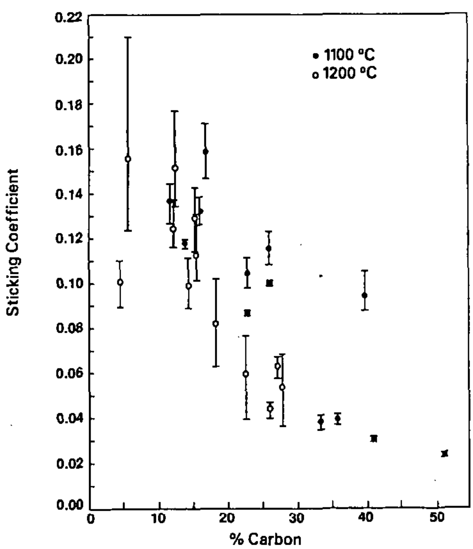

Figure 6: Sticking Coefficient vs % Carbon in Ash, Arkwright Bituminous Coal

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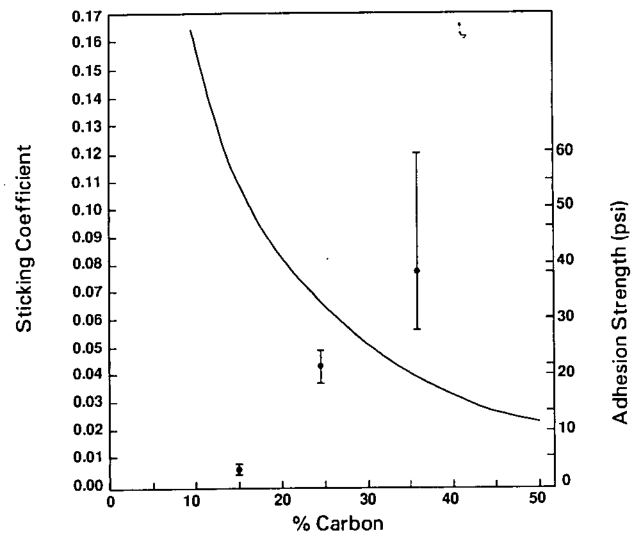

Figure 7: Adhesion Strength vs % Carbon in Ash Arkwright Bituminous Coal, T = 1100 °C

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